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PATH PLANNING FOR NON-PLANAR ROBOTIC ADDITIVE MANUFACTURING

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Abstract

As material extrusion additive manufacturing continues to mature, there is increasing need for an extrusion path planning ("slicing") method that takes full advantage of the abilities of many-degree-of-freedom systems like those used in Robotic Material Extrusion (RoMEX). These systems can create engineering parts with complex geometries and improved mechanical properties by utilizing non-planar curved layers, part-region-specific extrusion parameters, and support-free printing. This paper explores the application of 3D surfaces (demonstrated here with an upward pointing cone) as the basis of non-planar layer generation without the need to decompose the object into regions. Creation of these toolpaths incorporates key principles from planar, multi-planar, and active-Z path generation methods with attention paid to variable layer thickness, extrusion angle control, and overhang angle. The primary result of this work is a method for the generation of curved extrusion paths forming layers of arbitrary shape for arbitrary part geometry, based on a novel combination of existing best practices present throughout the available literature.

1. Introduction

Material Extrusion (MEX) creates parts, typically from thermoplastics, layer-by-layer [1]. The technology has gained widespread use with the adoption of hobby-level MEX desktop printers. While these printers, and their larger and faster industrial counterparts, have shown their strengths creating quick prototypes and models, rarely are they used for final production parts without postprocessing. The need to balance print time versus layer thickness often leads to rough surface finish. These parts also tend to be low-strength due to low infill percentages (more print time compromises), planar layers with minimum surface bonding area, and singular material choice. These typical planar/gantry prints also typically require support material that wastes print time and material, as well as marring the part surface they support. Overall, these printers excel at creating quick, draft-quality prints.

Attaching one of these same extruders to the end of an industrial 6-axis robot has gained increasing interest among researchers due to the robot's ability to control not only location but also orientation of the nozzle. This orientation control enables the tracing of complex 3-dimensional paths while maintaining a nozzle orientation perpendicular to the direction of travel. This ensures quality material bonding, prevents nozzle scraping, and maintains extrusion profile even while printing complex non-planar shapes. While gantry-style systems are capable of non-planar printing to a limited degree [2,3], robotic printing systems allow the nozzle to achieve this preferred orientation when printing curved layers of almost arbitrary shape. Advantages of this method include better part strength, surface finish, multi-material capability, and decreased part creation time [4–6].

This work demonstrates a method for the creation of self-supporting, curved (non-planar) layers for robotic material extrusion (RoMEX) including variable infill patterns and density. With the goal of creating strong, smooth, and functional end-use parts, these layers are used to generate extrusion paths for a simulated RoMEX system of arbitrary brand. While some have created their own part-specific toolpath generation techniques [7,8], others within academia and in the commercial space instead prefer to implement traditional planar part creation using these robotic extrusion systems [9,10]. The creation of curved layers (especially of arbitrary shape), including some level of infill control, for use on a generalized RoMEX system has not been seen in previous works. Systems such as this may enable MEX parts to find end use at lower cost than metal parts, but only if these systems take full advantage of the strengths of the hardware and software platforms.

2. Identifying Slicing Needs and Characteristics

Six major design aspects for RoMEX extrusion paths have been identified in literature: (1) curved non-planar layers, (2) variable material extrusion rate, (3) nozzle orientation control, (4) support material-free printing, (5) layer/load alignment, and (6) collision avoidance each help ensure success of prints that properly leverage the advantages of a RoMEX system. Table 1 highlights selected previous works that present solutions to at least one of these aspects. Note that no solution found in literature takes all aspects into consideration, and Curved Layer design is rare.

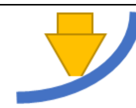
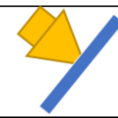
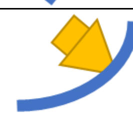
Table 1. Six aspects of non-planar path generation for RoMEX applications highlighted in literature. (*with modification or limitation)

	Variable Extrusion Rate	**Curved Layer**	**Nozzle Orientation**	**Support-Free**	**Layer Alignment**	**Collision Avoidance**
Bhatt 2020 [11]	N	N	Y	Y	Y	Y
Feucht 2020 [12]	Y	N	Y	N*	N	N*
Huang 2019 [8]	N	Y	Y	Y	Y	N
Khurana 2020 [2]	Y	N	N	N	Y	Y
Kubalak 2020 [7]	N	Y	Y	N	Y	Y
Meisel 2022 [13]	N	N	Y	N	N	N
Mitropoulou 2020 [14]	N	Y	Y	Y	Y*	N
Wu 2017[15]	N	N	Y	Y	N*	Y
Wuthrich 2021 [16]	N*	N	Y*	Y	N*	N

2.1.Curved Layers

Robotic material extrusion can print truly non-planar (curved) and multi-planar layers. Although visually interesting, this also has numerous applications from an engineering perspective. Aligning extrusion paths or “roads” to be parallel with tensile loads has been shown to increase strength of printed parts significantly [17,18]. This could be achieved by either curved layer design or in some cases by multiplanar slicing strategies where different regions of a given part are printed in a planar fashion, but the planes used in those regions may or may not align and with the build plate [15]. This is contrasted with traditional planer slicing methods that keep all layers perpendicular to the build plate at all times. These curved layers also allow for conformal printing on non-flat surfaces such as helmets, formwork for concrete or composites casting, and advanced electronics [4,13,19,20]. It also allows materials and print parameters to vary spatially and to better serve the design intent of the part. Some of the layer-generation techniques seen in literature use planes, stress-fields [7], surface path spirals [14], cones [16], or arbitrary surface geometry [21] to determine layer separations. Many authors have proposed various approaches to generating non-planar toolpaths, some specifically for robot-based 6 DOF systems. Often, these include one or more concepts seen in the generation of curved layers with orientation control but are limited in some sense, often by motion system degrees of freedom (nozzle orientation control). Table 2 shows a selection of different approaches.

Table 2. The four major approaches to MEX nozzle orientation.

Name	Nozzle Orientation Control	Planarity	Diagram
Planar	Z-Locked	Horz Plane Only	
Active-Z	Z-Locked	Non-Planar	
Multi-Planar	Unlocked	Planar	
Curved Layer	Unlocked	Non-Planar	

2.2.Variable Extrusion Rate

One of the primary parameters that needs to be controlled in robotic material extrusion is that of extrusion rate. The rate at which material exits the nozzle orifice determines not only pressure upon the substrate, such as previously built layers, which impacts part deformation, but also the bond strength by way of affecting the width of the extruded profile [22]. Bartolai et al show that, once contact between extruded filaments or "roads" is made, it is the temperature of the material that primarily drives the polymer chain entanglement that is bonding [18]. Together with extruder travel speed and substrate offset, extrusion rate also controls layer height and the possibility for under-/over-extrusion on features such as sharp corners. All these factors are important in planar printing but arguably even more so in geometrically complex nonplanar applications where unwanted extrusion variation can compound in unpredicted or complicated ways. A slicing algorithm that can intelligently leverage variable extrusion rate also unlocks possibilities such as multi-resolution printing and nonplanar applications using feature-dependent layer height [23,24].

Given the three-dimensional nature of curved-path planning, the task is sometimes approached as a volumetric one. Using volumetric elements (e.g., regularly shaped voxels) is one way to design local part path-varying extrusions in a part although it requires the ability to print with variable extrusion rates. This however can lead to complications in terms of determining travel order from element to element and can require some combination of interpolation between element center points and changes in extrusion rate. These become difficult to produce with existing off the shelf extruder hardware [7] because changing of flow rate is a dynamic process that takes non-zero time to settle. For example, if the flow rate is to increase, it takes time for enough filament to be fed into the extruder to increase internal pressure thus increasing flow [25]. This increase in flow also increases the cooling rate of the filament heater which must adjust. In a motion scenario such as that seen in material extrusion, including RoMEX applications, it is acknowledged that changing travel rate while keeping extrusion rate the same has lower latency and is thus also the preferred adjustment here [26]. Prusa Research has been one of the first to release a printer that has integrated some of these dynamic extrusion factors into their execution algorithms, albeit at the machine, rather than slicer level [27]. These two factors will likely see adaptation from the gantry-MEX to the RoMEX space as they allow increased extrusion accuracy through the cancelation of mechanical ringing and more accurate flow rate control respectively [28].

2.3.Nozzle Orientation

Authors researching a range of MEX materials have reported how nozzle orientation relative to extrusion path has a direct impact on surface quality both locally at the nozzle tip (affecting bond) and on the surface of the finished part. This is primarily caused by the corners of the nozzle tip scraping the top of previously deposited material[29]. To ensure maximum part strength (as characterized by maximum inter-layer bond strength), nozzle orientation should remain perpendicular to the substrate upon which material is being extruded [2,3,30,31]. This ensures proper pressure and contact is applied between the hot freshly extruded material and the colder layer beneath it to which bonding is essential [25]. Active Z slicing used on traditional Z-locked gantry-type printers allows for limited non-planar deposition; however, overcoming this limitation to ensure extruder orientation simultaneously normal to the motion path as well as the substrate is one of the primary drivers behind the adoption of RoMEX systems [9,20,32].

2.4.Support-Free

Non-part support material is often required by the logistics of traditional material extrusion systems. This added material must be manually removed and not only extends print times and wastes material, but it can also leave poor surface finishes on the parts themselves [16]. Support material can be avoided by ensuring surfaces are less than 45 degrees from gravitational vertical, sometimes by reorienting the build plate [15], or by designing part geometry with minimal or self-supporting overhangs [11,16]. As these systems are either complex or produce unwanted constraints on the part design space, conical slicing was created as a reimaging of the overall layering concept. Such slicing has been achieved by taking a mesh file such as an STL, conically warping it by moving the extremities furthest from the origin upward, slicing the part using planar-slicing methods, and then applying an inverted warp operation. Although this does create self-supporting, roughly conical layers of arbitrary geometry, it also creates geometric errors, does not allow for specifying layer alignment, and is limited to one layer shape [16]. While rafts, brims, and skirts may still need to be added during curved-layer RoMEX implementations, more complex layer shapes often allow for fast, support-free printing while overcoming these limitations to create higher quality parts [11,15,16,33]. However, if slicing algorithms designed for traditional planer printing are not sufficiently modified to remove this consideration for a many-degree-of-freedom system, this benefit is unseen. It is for this reason that nonplanar pathing algorithms for robotic material extrusion systems often benefit from being specifically designed for that task as opposed to modifying an existing 2.5D slicing approach.

2.5.Layer Alignment

A wide variety of structural improvements can be made by orienting MEX part layers. Often this is done with application load states in mind. Khurana et al showed that these improvements include a 40% increase in flexural strength, 80% increase in elastic stiffness, and a 100% increase in tensile strength [2,3]. This is primarily due to the strands of deposited material having higher tensile strength than the bonds perpendicular to those strands (i.e., between layers). A path planning algorithm that takes this into consideration can replicate traditional slicing methods by using planes parallel to the build plate or those driven by determining in which orientation the parts should be oriented for maximum strength. This is often done by aligning extrusion paths to tensile loads in parts [6,34]. Path/layer alignment may also be important if material properties while printing (i.e., viscosity) dictate a closer observation of path orientation relative to gravity. This is important when printing materials such as concrete that have a defined set time that is unable to be modified via external rates such as increase curing light exposure or external cooling rate [35].

2.6.Collision Avoidance

One further complication of a RoMEX system doing curved-layer printing is that of tool/part collision. Whereas planar printing avoids this issue by not crossing below the height value of the current layer, curved-layer path-planning algorithms must take extruder position and potentially even robot pose into consideration as to avoid accidental contact between any printing hardware and the in-progress print [15]. Fortunately, the collision avoidance aspect of curved-layer generation has seen significant research [29,31]. Although industrial robot control algorithms often take self-collision into consideration, any sufficiently complex non-planar path planning must take its own history (material printed up to that moment) into consideration. Work has been done in using simplified bounding box or reduced feature models to simplify collision prediction calculation. Another approach is to use distances between major extruder vertices and part voxels to cull regions where collisions are unlikely, but this is not easily implemented [11]. One limitation seen in many of these approaches is that low fidelity in these models can lead to collision prediction false positives [11,29,31]. Researchers have yet to collectively settle on a single collision-prevention technique of choice, preferring to explore new potential solutions of their own.

3. Proof-of-Concept Path Planner

Key findings across a spectrum of existing work related to the six important aspects in Section 2 were evaluated independently from their peers and selectively integrated into a single RoMEX path planner. These approaches, concepts, and tools form a strong foundation of previously vetted cornerstones upon which to build. Although many of them have been heavily explored, choosing specific core concepts from larger works in literature was the focus, resulting in a novel combination of existing best practices present throughout the available literature. Choosing concepts that were both successful and that could be readily adapted to this work was important in synthesizing successful components from specialized systems into a more generalized single framework of synergistic modules.

3.1.Layer Schema

One of the most exciting areas of research in the MEX community of late has been that of truly non-planar, curved layers. Specifically, Rene Mueller's research into arbitrary layer shapes [16,21] has proven insightful for the advance of this work. However, where that work is focused on systems limited to gantry-style Active-Z printing, the concept can be expanded into RoMEX. Curved layers can be created from a non-planar, semi-arbitrary surface that exists in 3D. This surface serves as a line of demarcation between layers. A stack of these layers can be separated by either a static distance or a distance that changes either inter-layer, as used in adaptive slicing, or intra-layer, yielding variable layer thickness. As the same layer shape is usually stacked repeatedly, one of the only limitations in layer shape is that that the surface shape never passes vertical as this would create unprintable, superimposed layers. This regularized stacking concept can be conceptualized by envisioning a stack of traffic cones; the same three-dimensional shape is repeated along a common axis with regular spacing. This is a generalized form of the principle used in planar slicing, but here the surface is not a horizontal plane, but a cone or other shape used to slice an object into layers.

Although this principle is accepting of a wide variety of surface shapes (including hemispheres [3,7]), the cone has been chosen for this demonstration for several reasons. First, as a geometric primitive, the shape is easier to implement for demonstration than an arbitrary (e.g., trigonometric) one within SolidWorks. Second and more importantly, the sloped sides of an upward pointing 45-degree cone form a safely self-supporting layer that does not require the printing of sacrificial support material [21]. Third, conical layers provide a significant increase in the layer-to-layer contact and mechanical interlock areas over flat planes. This in turn increases the inter-layer bond strength and leads to stronger parts [3,18]. In particular, it allows for clear and uniform angling of the inter-layer boundaries to better align with tensile forces along the vertical axis of the part, should those be of interest in a given application.

The proof-of-concept work described here also demonstrates the importance of several other aspects from Section 2. One of these, variable extrusion rate, is demonstrated by applying a finer, lower extrusion rate tool path on the exterior of the part. Likely applied at a lower speed, this outer "shell" uses a shorter layer height to create an accurate, smoother surface finish as seen in blue in Figure 1. Depending on the part volume, maximizing the deposition rate of the rougher core and maximizing the smoothness of the skins may prove valuable in improving the overall print time as coarser parts can be printed faster. Core perimeters are shown in dark orange in Figure 1. This is further improved with the nozzle orientation abilities of RoMEX as dynamic nozzle orientation allows for both fewer shell extrusion paths (bead width is wider than layer thickness) and smoother surfaces (the nozzle tip flat naturally irons the surface as opposed to stair stepping). This active reorientation also prevents the nozzle from scraping the previous layers, which has been a concern in Active-Z research, by keeping the nozzle normal to the extrusion path as often as is feasible. By applying outer skins after building the inner core, freshly extruded material fills gaps between core layers. The added heat at the layer-layer boundary also further enhances the polymer weld[17,18,36]. Eventually, these outer layers may also be applied in a different material, with different extrusion settings, or even by a different nozzle. Overall, applying a fine layer of shell material perpendicular and over a coarse but strong part core leads to a strong part with smooth outer surface.

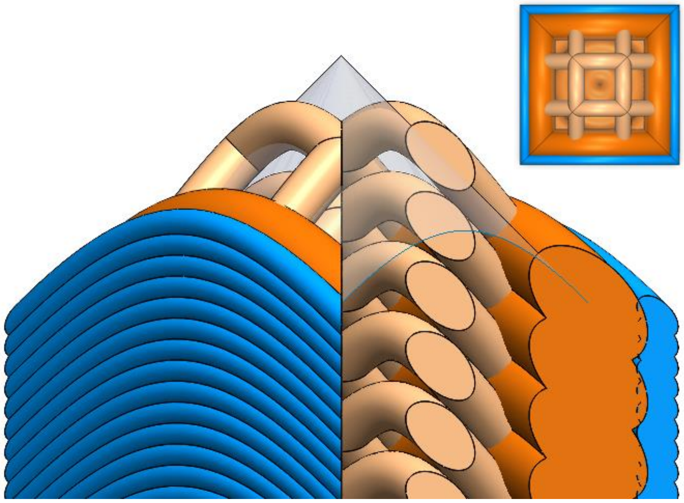


Figure 1. Conceptual demonstration of extrusion path types. A virtual cross section of a part mid-print showing an outer shell with fine layers (blue), coarser core perimeters (dark orange), medium thickness low density rectilinear infill (light orange), and the topmost conical core layer (transparent grey). Note that the two core extrusion path types, core perimeter and infill, share a layer surface (the cone) that is not shared by the shell paths. Inset shows top view.

3.2.Mechanical Considerations

Arguably the greatest strength of RoMEX is its ability to create highly curved layers. For quality, this must be done while avoiding colliding the nozzle with the layers and maintaining ideal extrusion orientation via layer alignment. Although others have established the usefulness of aligning layers to tensile loads [3], directional surfaces [2,3], or optimized surface topology [7] for example, these approaches tend to be specialized for part shape or application. For the exploratory work in this paper, a focus was placed on a resistance to gravity during printing for support free printing. MEX parts tend to be strongest when forces are aligned with extrusion paths (i.e., roads) and cone-shaped layers help to orient paths/layers in more universally productive directions (radial and axial) than planar layers (XY plane only) while also helping make overhangs printable.

Although other options have been presented in the past few years, the concept of conical slicing combined with the arbitrary layer shape shown in work by Mueller [16,21] make a powerful combination. Together they show that a cone or similar shape may be chosen such that the layers are self-supporting during printing. This serves two functions: time and material need not be wasted printing and then removing supports, and the part surface touching supports remains unmarred by their use. The final aspect considered in this project was that of collision avoidance. Specifically, avoiding collisions between the robotic extruder and itself, the build plate, etc., and avoiding extruder collisions with the part. In using a modern robot simulation and control program, the former is largely already solved. The latter is solved through an insight gained from planar MEX. When printing planes of material, one method to avoid part collisions is to prevent the extruder from crossing the current, active layer into a previous one even if that that space should be vacant. This same principle may be generalized to non-planar layers although the layers are more complex in shape. This process takes place as a consequence of sequentially slicing a part one layer at a time. In the simple shapes tested here no further issues were discovered although a more robust collision check should be included in future work.

3.3. Implementation

The aspects discussed above were implemented through a combination of two software programs: SolidWorks (Dassault Systèmes), a mechanical design tool, and RoboDK, a manufacturer-agnostic industrial robot simulation and programming package. SolidWorks was used for the geometrical work of part import or creation, slicing, and path generation. RoboDK was used to turn these paths into robot motions specific to a user's hardware. A special focus was placed on making this system as manufacturer independent as possible, both in terms of modeling and simulation. SolidWorks can import a wide range of file types and the automation performed in this tool is easily modified for other major modeling tools as it uses the common VBA programming language, which is also used by CATIA and others for automation. RoboDK maintains a library of most robots from most major manufactures while also allowing users to create their own. This approach should allow future users to readily convert the automation and hardware environment described below to their specific application. Generally, the process of creating a curved layer extrusion path plan for RoMEX applications in this implementation is divisible into three segments of thought and proceeds as shown in Figure 2.

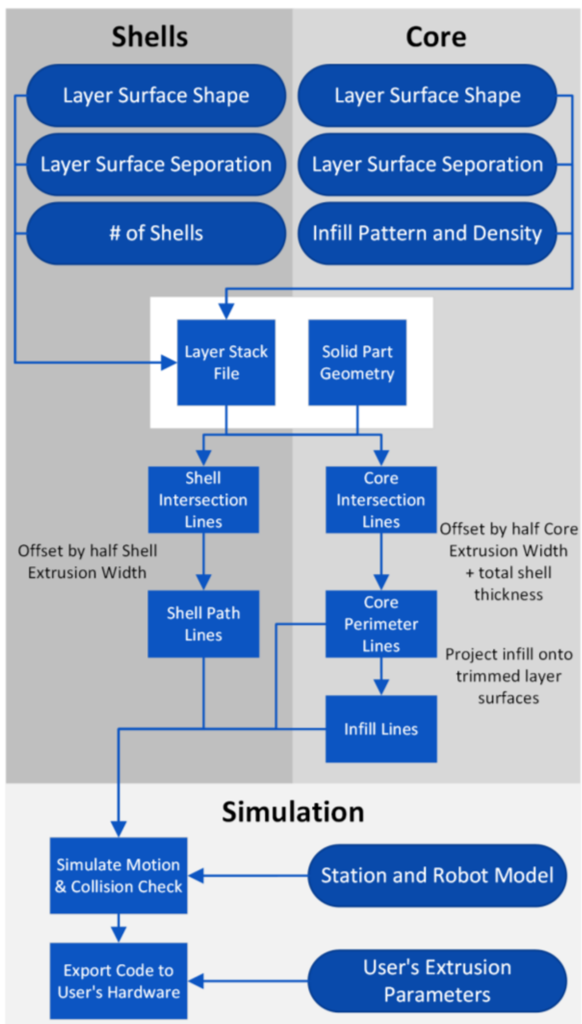


Figure 2. The three conceptual sections of this work to generate curved-layer extrusion paths including inputs and flow of dependencies.

The first step in creating curved-layer extrusion paths using this method is to collect important data from the user about how the part is to be sliced. For shells, this consists of layer surface shape, layer spacing (both of which may vary), and number of shells. For the core, this consists of potentially varying layer surface shape, layer spacing, and infill. For the latter, infill pattern and density can also vary across the volume to optimize, for example, regional part loading or mass distribution. For reasons of demonstration, a 45-degree, upward pointing cone is used for both shell and core layer shape which are spaced at static distances of 0.07mm and 0.3mm for shell and core layers respectively. A 50% density rectilinear infill was chosen for clarity of demonstration. The user must also specify the extrusion width for each the core and the shell print parameters on their system. Here a width of 0.45mm for the 0.07mm shell layer height and 0.5mm for the 0.3mm core layers is assumed. These values are based on the default settings of the publicly available PrusaSlicer gantry/planar slicer for the typical 0.4mm orifice nozzle.

Once these slicing parameters are chosen, two series of these layers are stacked along the Z direction of the design volume, one for the shell layers and one for the core layers. Both stacks should completely encompass the build volume in all three dimensions. In the case of the core layers, the infill for that layer will later be projected from a plane or other surface where it was designed onto its corresponding layer in the stack. This will be done at the end of the process. Future work will interface with the user and generate the required layer stack file and infill on demand. With the shell layer stack and the core layer assembled, the process is now ready to reference the actual part geometry to be printed. For the time being, this work requires that the user manually confirm that the part is centered and aligned with the Z axis of the layer stacks and that it is completely within the build volume of their RoMEX system. The part chosen to demonstrate this method of creating curved-layer extrusion paths is a cantilevered "L" shape with an unsupported overhang seen in Figure 3a. In planar MEX printing, this overhang would require supports to be generated, printed, and removed. Here those steps are unnecessary thanks to the conical layer shape chosen.

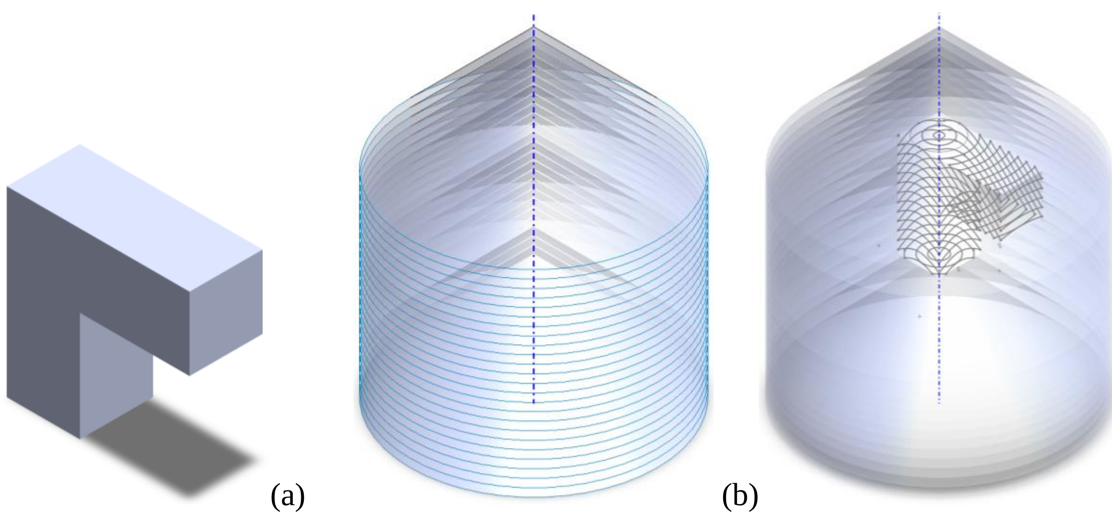


Figure 3. Cantilivered "L" part (a), example layer surface stack (b), extracting intersection lines between the part faces and the layer surfaces along with the center axis (c)

The intersection between the shell layers and the surface of the part are 3D lines that exist on both surfaces. Figure 3c shows example Intersection Lines, which demonstrates the concept as it applies to both Core and Shell Intersection Lines. Insetting these lines toward the center of the layer shapes (toward the Z axis) allows the Shell Path Lines to take the shell extrusion width into consideration. Specifically, by shifting the final extrusion path from the actual surface of the part (the Shell Intersection Lines) inward by half the shell extrusion width along the respective layer surface the outer surface of the final part should be dimensionally accurate. If more than one shell is desired, the same shell layer surface stack may be utilized but further insets should be whole steps of the shell extrusion width.

This same insetting procedure is followed using the core layer stack and part geometry to create the Core Intersection Lines and Core Perimeter Lines. This process begins to differ in that the inset distance is equal to half the core extrusion width *plus* the total thickness of all shell layers. This should put the outside edge of the printed Core Perimeter Lines adjacent (0% overlap) to the innermost edge of the Shell Path Lines if they should happen to share a layer surface. To create parts that have strong shell-core bonding, this overlap percentage should be increased. The last to be produced, the Infill Lines are created by using the Core Perimeter Lines to trim their corresponding core surface layer. After this operation, the infill design is projected onto the now trimmed surfaces. This results in trimming the core layer stack to only the layer surface areas that lie within the core of the part. As the infill of this demonstration print is the same on all layers, the same sketch may be projected onto each of the core layers. This infill sketch was designed such that it covered the entire build volume of the hypothetical printer and used the above extrusion widths to determine extrusion path spacing for the chosen density. The methodology here has been ordered such that this process also trims the infill pattern by projecting it. When printed the Infill Lines have end points that coincide with the Core Perimeter Lines (100% overlap), although this can be adjusted either in SolidWorks (using the same insetting technique seen above applied before trimming the layer) or by instructing RoboDK to end each infill line early (a built-in option). Figure 4 shows the important paths for one set of the lines to export.

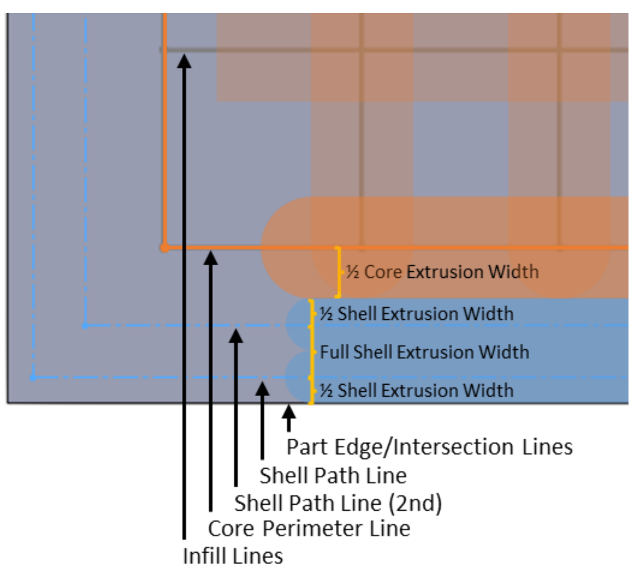


Figure 4. Graphical description of line locations and their offsets including Shell Path (2 shells shown), Core Perimeter, and Infill Lines. Shown along the Z axis of the part (“top down”).

One can see from this small segment how complex performing these operations manually becomes with larger parts. With that in mind, this process can be automated using SolidWorks' macro tools using VBA as discussed above. Once the primary task of creating these lines is complete, they are exported from SolidWorks into RoboDK. This is accomplished very simply by way of their SolidWorks Add-In or by exporting the paths from SolidWorks and importing it into RoboDK. This is also a time to ensure sufficient accuracy is maintained when transferring paths between programs (settings) as the hope of this work is partially to improve fidelity through slicing better than when using an STL.

Once these three important series of curves and an existing model of the robot and extruder are imported into the simulation package, a curve-following orientation plan ("Curve Follow Project" in RoboDK) can be constructed to convert those paths into motion. This project type is used as it allows the software to actively adjust the nozzle orientation while a 3D printing project forces the nozzle to remain locked to the Z-axis of the reference frame. The simulation should be set up to allow the extruder nozzle to rotate about its primary axis in order to allow the maximum amount of flexibility during path creation. The primary goal of this step however is to ensure the nozzle stays as normal to the imported curves (and thus the underlying layer surfaces) as possible to create clean and consistent layers for both smooth surface finishes and for proper inter-layer bonding. Internal collisions between the robot and the structure of the space (such as build plate) are avoided thanks to importing their respective models into the workspace of RoboDK. It is suggested that the print order proceed from core perimeters, to infill, and finally the outer shells. By printing the core perimeters first, the material of the infill and shells have something to bond to while being placed. Due to the different layer thicknesses of the shell and core layers, multiple shell layers will likely need to be added for each core layer. An effort should be made to extrude shells up to but not further than the current core layer in order to avoid collision with previously extruded material. From here, the user uses the RoboDK toolset to integrate with their specific system.

3.4.Case Study Results

Curved, non-planar, MEX toolpaths were generated using arbitrary part geometry, layer shapes, and infill shape. These paths enable a many-degree-of-freedom RoMEX printing system to create stronger parts with better surface finish, better inter-layer bonding, and no supports by leveraging the nozzle-orientation capabilities of these systems. Six important aspects of path planning for non-planar robotic additive manufacturing were identified and addressed by the slicing strategy demonstrated. By intersecting user geometry with a stack of layers surfaces that are not planes (such as the 45-degree cone used here), material can be laid down with its strongest direction better aligned to a wide range of loading directions. This is due both to extrusion-path/load alignment, but also due to an increased inter-layer bond area over gantry-type MEX printers [3]. Thicker core layers also cool slower, allowing for better polymer welding to take place [18,36].

The demonstration produces an example part consisting of one shell, one core perimeter which is essentially another (if coarser) shell, and infill. The layer shape, material, and thickness can vary not only throughout the volume of the part, but the inner/outer layers and infill of the object may vary independent of one another. This is one way of producing parts that have strong, quickly printed cores with comparatively smooth, high-fidelity shells. This is a first-order approximation of the concept of variable extrusion rate that future work will expand to vary layer thickness across a single layer. The simple rotated “L” shape of square profile is comparable to that seen in Mueller’s non-planar work [21]. This cantilevered beam that can be seen in Figure 5 highlights the advantage of support-free printing via curved layers. It also makes the case for active nozzle-orientation control as layers with such strong curvature require a large range of orientation motion to prevent nozzle tip scraping or degradation of the extrusion profile or bond.

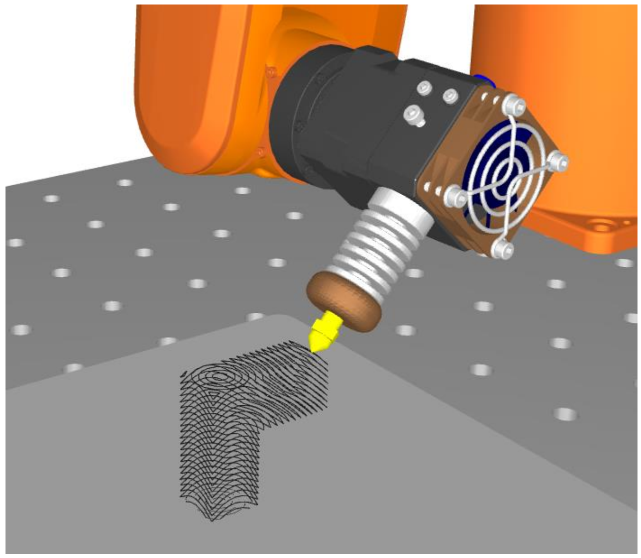


Figure 5. RoboDK robot station showing ideal nozzle orientation for that path segment. Core Perimeter Lines shown alone for clarity.

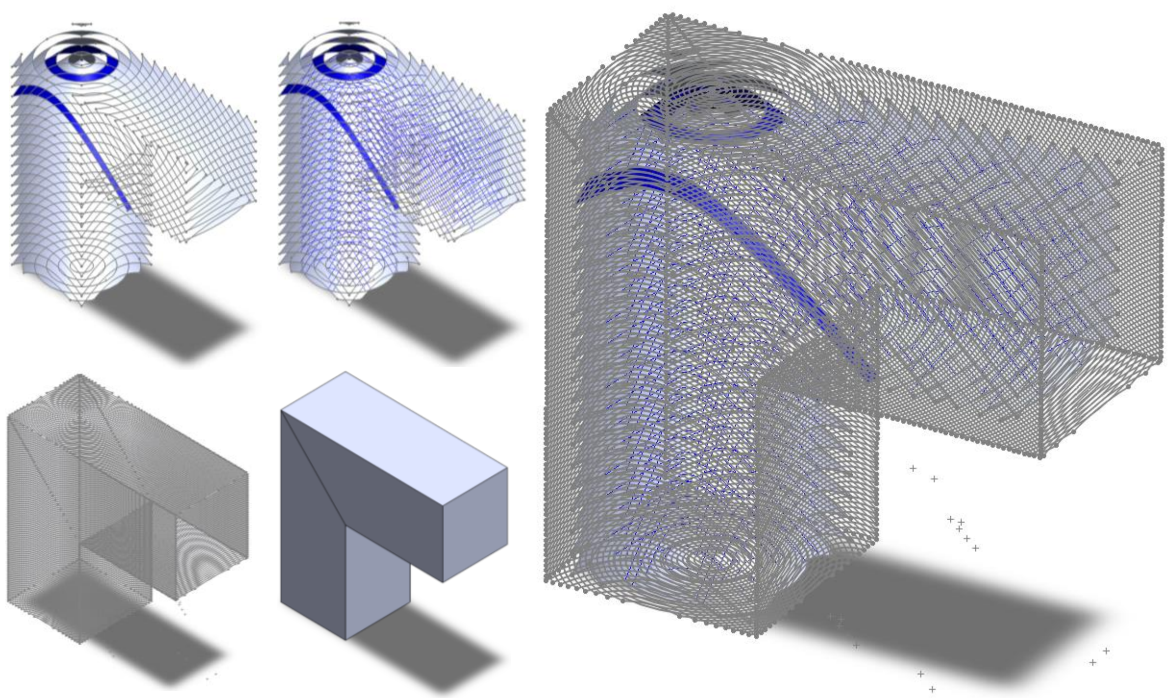


Figure 6. Final part using parameters from Section 2.3. Core Perimeter Lines with exemplar blue highlighted conical layer surface (a), Core Perimeter Lines (grey lines) and Infill Lines (blue lines) (b), Shell Path Lines only (c), original solid part (d), all three path types assembled (e)

4. Conclusions

RoMEX can greatly improve the functionality of thermoplastic parts, but these advantages require a new curved-layer path planning strategy designed with nozzle orientation in mind. The strategy presented here shows and demonstrated in Figure 6 represents one method for creating complex, non-planar extrusion paths and layer shapes that promote part strength, surface smoothness, and support-free printing. A novel contribution consisting of using pseudo-arbitrary surfaces to create curved layer RoMEX toolpaths including infill has been demonstrated. Several benefits come with utilizing this method for creating non-planar extrusion paths using this method in particular. While printing objects with curved layers in general tends to allow parts to be printed with few if any supports, this method's approach to separating shell/core parameters allows greater inter-layer bonding, shorter production time, and smoother exteriors. Omitting support material saves both post-process time and material while different layer thicknesses customizable infill and layer shape further decrease on-printer time. Object fidelity is also improved compared to typical planar printing as this method requires no conversion to intermediary file type, and curve fidelity is kept high during transfer between programs. Finally, as this method utilizes pre-generated surfaces to split layers, the semi-automated process is designed to be quick and user friendly.

It should be noted that this first implementation of the methodology has known limitations, both in terms of extrusion and motion. One example of a motion-related restriction is that of collision and robot singularity avoidance. In future work, a more robust part/robot collision prediction and avoidance system should be implemented to allow for more complex parts to be printed with confidence. Singularities, points where the robot control algorithm encounters errors due to multiple kinematic solutions, are currently left to RoboDK and the user to resolve as the exact details of the user's kinematic system vary. The same is true with layer shapes (i.e., cone) that have sharp points as these may lead to motion incongruities and errors. That said, this work could benefit from being implemented on a physical RoMEX system to gather valuable real-world data about performance and future improvements.

Future versions will generate the layer surface stack on command given inputs like cone angle, automatically modify the infill patterns to achieve the requested density, and pattern these forms into a layer surface stack that can then be imported. This would further simplify the user experience and allow for greater control of slicing parameters. The current projection method for infill generation also leads to discrepancies in infill density in more vertical regions of the part. Automatic alignment of part and layers would also further the automation. The exact shape of these layers, including layer shapes that vary across differently loaded regions of a given part, as well as the benefits of each of these layer shapes still needs to be characterized. This concept may be furthered by conceptualizing more advanced designed layer shapes that are non-regular and vary by region within the part or intra-layer. The implementation of intra-layer variable material extrusion rate would allow for more complex layer geometry (e.g., thick toward the center and thin toward the perimeters) and thus potentially greater improvements in print time and inter-layer bonding. Print order of islands are currently unoptimized and a further check needs to be performed to check that unusual geometries work well with all layer shapes. There are also hypothetical geometry/layer shape combinations that necessitate minimal supports (floating islands) or would need local layer shape adaptations to be made printable. While there are obvious improvements that can be made to this non-planar path planning technique, the base principles explored here have shown significant merit over the current state-of-the-art that uses planar techniques even with a higher degree of freedom motion platform.

5. References

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